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ORIGINAL ARTICLE

Multilayered visuo-haptic hair simulation

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Abstract Over the last fifteen years, research on hair simulation has made great advances in the domains of modeling, animation and rendering, and is now moving towards more innovative interaction modalities. The combination of visual and haptic interaction within a virtual hairstyling simulation framework represents an important concept evolving in this direction. Our visuo-haptic hair interaction framework consists of two layers which handle the response to the user's interaction at a local level (around the contact area), and at a global level (on the full hairstyle). Two distinct simulation models compute individual and collective hair behavior. Our multilayered approach can be used to efficiently address the specific requirements of haptics and vision. Haptic interaction with both models has been tested with virtual hairstyling tools.

Keywords Hair simulation · Haptic rendering · Multimodal perception · Interactive modeling

1 Introduction

Hair simulation research has been quite intriguing and challenging for almost two decades. During the last few years there have been successful developments of new concepts related to both photo-realistic visualization and real-time animation of hair. With the advances in computer graphics, the research is now moving towards more innovative interaction modalities. The combination of visual and haptic interaction within a virtual hairstyling simulation framework represents an important concept evolving in this direction.

Haptic defines what is related to the sense of touch. This sense can be roughly divided into two different kinds of information. On the one hand, we perceive cutaneous stimuli, which correspond to the tactile sensations perceived by the skin, like temperature or roughness. The reproduction of these tactile cues still requires the solution of challenging problems concerning the generation and rendering of adequate stimuli to the human fingertip skin through appropriate hardware. On the other hand, we perceive kinesthetic information, corresponding to the forces felt and the perceived posture or motions of the arms and hands. This sensing modality is more and more integrated in virtual-reality systems, since recent advances in haptic technology have significantly improved the spatial and force resolution of available force-feedback interfaces while reducing their development costs.

The reproduction of virtual forces provides useful sensory information for a large number of applications such as VR-based training, virtual surgery, 3D graphics and entertainment, and can significantly improve the interaction with 3D deformable objects. In the context of virtual hair, sensing an appropriate force-feedback while creating a new hairstyle for a virtual human can significantly increase the application usability.

1.1 Contributions

In order to exploit the advantages of the sense of touch, it is essential to explore the issues related to the perceptual

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mechanisms involved when handling real hair, and to adequately convey the appropriate stimuli to the user through a simulation framework which efficiently addresses the different requirements stemming from the visual and the haptic sensing modalities. Moreover, the visuo-haptic simulation of hair calls for real-time performance—a particular challenge because of the hair's strong anisotropic dynamic properties and the high requirements in terms of computational power. To address these issues, it is important to efficiently reduce the computing costs without affecting the simulation accuracy. To achieve these goals, our approach comprises the following contributions:

- Our work is carried by studies on real physical hair properties investigating hair's handle-and-feel. We discuss the most relevant hair properties to model in the context of visuo-haptic computer simulation considering both the hair's mechanical behavior and its haptic perception.
- Our visuo-haptic hair interaction framework consists of two layers which handle the response to the user's interaction at a local level (around the contact area), and at a global level (on the full hairstyle). These two layers specifically address the requirements of vision and haptics and run at different rates.
- The *local interaction layer* models the contact between the user's tool (e.g. a brush) and hair strands, which are animated according to individual hair strand mechanics. We propose a simple and fast model to simulate individual hair strands based on segmented helical rods and compute contact forces according to haptically relevant hair properties.
- The *global dynamics layer* displays the large-scale behavior of hair and handles contacts with clusters of hair strands. We base our research on a free form deformation model which offers a good level-of-detail control, fast interpolation during animation and sufficient versatility for simulating any kind of complex hairstyles.

1.2 Organization

This paper is organized as follows: Sect. 2 provides an overview of existing hair simulation techniques, divided into models describing individual hair strand mechanics and large-scale hair dynamics. Section 3 discusses the use of physical properties of hair in the context of visuo-haptic hair simulation, distinguishing between the hair's mechanical behavior and its haptically relevant characteristics. The following two sections present our mechanical models for visuo-haptic hair simulation, with Sect. 4 describing the features of our local interaction model and Sect. 5 discussing the global model. The paper ends with Sect. 6 giving some concluding remarks and prospects of future work.

2 Hair animation techniques

Research on hair simulation has made great advances over the last fifteen years, and different computer animation models have been used to approximate the behavior of hair in a realistic way. But the physically correct reproduction of hair behavior during real-time animation and interaction is far from being achieved. Some of the proposed approaches consider hair as a finite number of strands and implement different techniques to animate single strands. Other approaches describe the collective hair properties and e.g. define hair as a set of particles, model the volumetric changes of the whole hairstyle, or propose a level-of-detail simulation hierarchy. A survey on hair styling, simulation and rendering has recently been given by Ward et al. [1]. Of particular interest for us is the identification of simulation models which are suitable for the visuo-haptic simulation of hair. We therefore analyze two types of techniques: those who model *individual hair strand mechanics* and those who model the *large-scale hair dynamics*.

2.1 Models for individual hair strand mechanics

Early work on hair animation modeled hair explicitly, computing shape and dynamics of each individual hair strand. This approach has proved to be especially suitable for dynamics of long hair, and after Rosenblum's mass-spring-hinge model [2] and Anjyo's projective dynamics solution [3], several variations have been proposed over the last decades. Although being quite realistic and easy to implement, however, these approaches are not appropriate for wavy hair and suffer from large computation time, which allows simulating only a limited amount of hair strands. Moreover, most of these explicit techniques animate hair in two dimensions, but are ill-suited for representing torsional motions and strong curliness. This was partially solved by approaches considering hair as chains of rigid bodies introduced by Hadap and Magnenat-Thalmann [4], which took into account individual hair mechanics including three-dimensional motions with support for torsional behavior. This model, however, required arbitrarily increased bending and twisting stiffnesses to maintain the curved rest shape under gravity. Moreover, the large computation time did not allow reaching real-time performance.

More recently, Bertails et al. have proposed to model the nonlinear behavior of single hair strands with Dynamic Super Helices [5]. The main advantage of this physically based formulation is the easy handling of curly hair (through the models' intrinsic definition of twist-and-bend), and the length preservation during deformation (as the model represents inextensible elastic rods). A super-helix is based on a continuous Cosserat curve discretized into helical segments and is animated with Lagrangian mechanics. It properly handles the dynamics of curls by modeling bending and twisting deformations and allows simulating a vast range of different hairstyles. Collision handling has been improved by the CoRdE model [6], which is also inspired by the Cosserat theory of elastic rods, but employs the finite elements method to discretize the continuous energies. This allows handling self-contacts such as complex knots for generic one-dimensional elastic objects.

Thanks to the intrinsic definition of curliness enabled by the inextensible Cosserat rod through its bending and twisting properties, and the possibility of tuning the corresponding stiffnesses within the model, hair simulation models leaning on the Cosserat theory of elastic rods seem to be the best candidates for representing the dynamic physical behavior of individual hair strands.

2.2 Models for large-scale hair dynamics

The human scalp is populated by around 150,000 individual hair strands. Reproducing the realistic dynamic behavior of a complete hairstyle taking into account individual hair structure and properties, as well as the various hair–hair interactions, is an extremely complex and expensive task in terms of computing resources. Therefore, several simplification and optimization processes have been studied in order to decrease the complexity and the computation time for calculating the large-scale dynamics of a full hairstyle. Most common solutions discard the attempt to consider each hair strand explicitly, but reduce the geometric complexity by grouping strands into wisp-, cluster- or strip-models [7–9], animate hair using loosely connected particles [10] or define the overall volume of a hairstyle and its dynamics through a free-form deformation lattice [11]. Especially the latter approach allows representing a broad variety of different hairstyles and overcoming scalability problems. Thanks to its high performance and versatility, this volumetric approach results particularly suitable for approximating the large-scale behavior of a full hairstyle.

3 Modeling physical properties of hair fibers for visuo-haptic hair simulation

Although the research community has proposed different ways of modeling and animating hair, no known hair modeling method is able to simulate the structure, motion, collisions, and other intricacies of hair in a fast and physically exact manner [1]. The reason for this lies not only in the complexity of the task or in the limited amount of computing resources. The lack of measured data specifying the mechanical behavior of large sets of different hair samples prevents to accurately simulate how changes in the hair physical properties will influence its motion and structure. Moreover, the knowledge about the way humans perceive the sense of touching hair has been almost neglected in the context of virtual-reality simulation and interactive hairstyling so far.

3.1 Physical properties of hair

Chemical and physical behavior of human hair has been extensively reported in the literature along with descriptions of the human hair morphology, composition and properties [12]. Hair fiber is mainly composed by keratins (65–95%), which are responsible for the remarkable mechanical properties of hair. These properties are dependent on time, temperature and humidity [13]. Common methods to assess alterations such as hair damages analyze color changes, hair shine, protein loss, and changes of mechanical properties [14]. However, there are currently no standard procedures for experiments with human hair, and the best methodology to use in these studies, as well as the number of replicates necessary to have statistically significant results, is still undefined [15].

In order to obtain a clear insight of the main parameters to consider when developing a virtual visuo-haptic hairstyling interface, a thorough review of the state-of-the-art literature in the hair science domain is a fundamental step to define which hair fiber properties can be considered more relevant when modeling the dynamics of hair strands and when reproducing the feeling of touching hair.

3.2 Mechanical behavior of hair

The mechanical behavior of hair is dependent on many factors that can be divided into four main domains: tensile, bending, twisting properties and their relaxation in each of the different modes [16]. We assume that in a hairstyling context, *tensile* hair properties can be neglected since natural interaction with real hair will not elicit forces able to produce visible tensile elongations. However, a pseudo-elastic behavior of hair can be observed when stretching curled hair fibers. This property can be modeled as relaxation of curliness, which in turn is expressed by a combination of bending and twisting. Concerning hair bending, there is good evidence that the hair's cross section plays a significant role in the strand's bending behavior. African and Caucasian hair strands have a strongly elliptical cross section (see Fig. 1), while Asian hair is generally less ellipsoidal. This leads us to the simplification of a hair strand as a non-circular one-dimensional rod, and we assume that single fibers will naturally tend to bend over their cross section's major axis only [17].

This consideration allows us to neglect bending over the fiber's minor axis, and reduce the main factors influencing the natural mechanical behavior of hair fibers to the following:

1. *Bending* only over the cross section's major axis
2. *Twisting* around its centerline
3. *Relaxation* from the two previous modes

Table 1 Correlations of objective measured data and subjective rating of different hair types [19]

Hair type	Positive ratings (%)	Maj. axis diameter (μm)	Ellipticity	Bending stiffness (10^{-9} Nm)	Frictional force (cN)
H1	41	93.1	1.36	7.59	0.64
H2	69	96.1	1.33	9.25	n/a
GA1	94	89.5	1.45	5.23	0.65
GC3	94	89.3	1.42	5.66	0.79

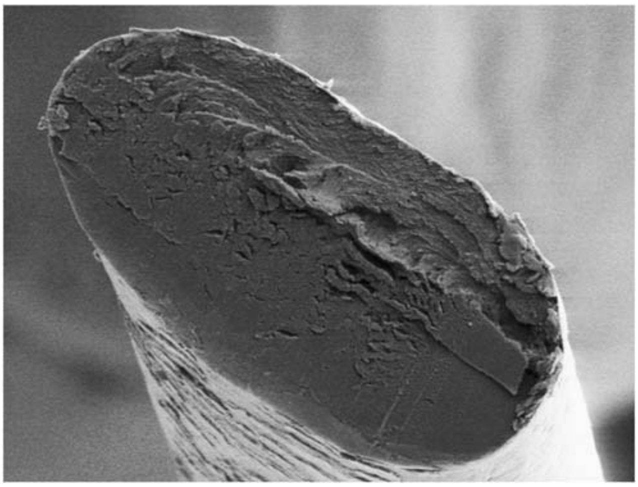

Fig. 1 Caucasian hair displays an elliptical cross section [18]

Without claiming exhaustiveness, a mechanical model for virtual hair simulation describing these hair fiber characteristics can provide a rough approximation of the *natural physical behavior* of hair strands.

3.3 Hair handle

Little is known about the way humans perceive light deformable objects such as hair fibers. Due to the importance of understanding the properties which characterize the sensations of softness or smoothness in real hair, researchers in the field of cosmetic industry have analyzed the specific physical and mechanical qualities of hair towards handle. *Hair handle* refers to the sum of sensations arising when stroking and touching hair, and depends thus on several hair fiber properties. Determining the correlation between fiber properties and hair handle can be of utter relevance when developing new hair-care products. Hair fiber properties can be measured *quantitatively* in an objective way through appropriate chemical, mechanical and optical means. Their *qualitative*, subjective evaluation can be performed by experts who professionally touch and feel hair for determining their handle. In a related research [19], "good handle" was associated with the adjectives "smooth," "soft" and "flexible," which is the case for hair with a low bending stiffness, low diameter, and high ellipticity. Negative adjectives determining "bad handle" were typically "coarse" and "blunt," with higher bending stiffness and diameter, as well as higher friction at the tip region. Table 1 presents an excerpt of the investigated properties summarizing this evaluation.

Following the cited research [19], the most relevant fiber properties towards hair handle can be identified as:

1. *Geometrical properties* of hair fibers such as cross-sectional geometry, ellipticity, diameter and length
2. *Bending properties* of single fibers forming a fiber collective
3. *Frictional properties* of hair fibers contributing to surface roughness

Hair handle can provide fundamental insight about the most relevant hair parameters to model when simulating the *haptic interaction with virtual hair*.

4 Local interaction layer

In our simulation framework, the local interaction layer defines the motion and contact behavior of individual hair strands during haptic interaction. The underlying hair model is based on a simplification of the Super-Helix approach discussed in Sect. 2. A hair strand is a discretized Cosserat curve modeled as an elastic rod composed of one or more helical segments (see Fig. 2). A major difference from the original model lies in the allowed degrees of freedom for each segment. The model proposed by [5] defines the twist and two curvatures per segment. Thus, it allows a broad range of possible motions for one-dimensional elements. Our main aim, however, is to reproduce the *natural* hair behavior. Following the relevant literature in hair science and cosmetics [17, 19], we assume that hair does not naturally bend over the minor axis of its cross section. Hence, for each hair segment we only model the twist and the bend [20]. Through this simplification we reduce the number of equations to solve by one third, compared to the full model, while preserving its important modeling properties concerning the intrinsic curliness and the bending/twisting stiffness.

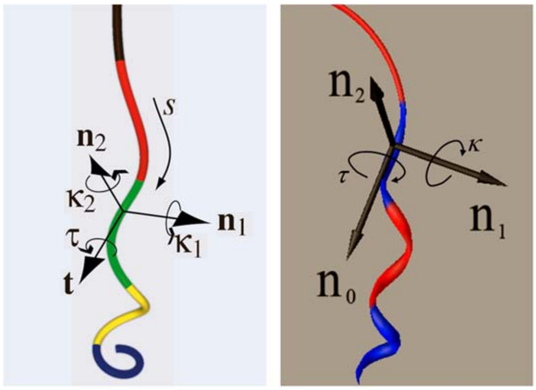

Fig. 2 Unlike a super-helix [5] (*left*), individual hair strands simulated with our local model [20] (*right*) display an elliptical cross section and are subject only to deformations caused by twisting around the centerline (τ) and bending over the major axis (κ)

4.1 Hair strand definition

We consider a strand of length L, divided into N helical segments. The twist and bend of segment S_Q $(1 \le Q \le N)$ depends on time and it is written $q_{i,Q}(t)$ for $i = 0, 1$. The numbers $q_{i,Q}(t)$ together form a vector of size $2N$ denoted $\vec{q}(t)$.

Curvature for the whole strand is then given as

$$\kappa_i(s, \vec{q}, t) = \sum_{Q=1}^{N} q_{i,Q}(t)\chi_Q(s)$$

for $i = 0, 1$, where $\chi_Q(s)$ is the characteristic function of segment S_Q.

The vector $\vec{q}$ allows us to compute the 3D position of the centerline of the super-helix, denoted $\vec{r}(s, \vec{q}, t)$. Each point on the centerline has an associated material reference frame, an orthonormal basis given by the orientation of the cross section at that point. We denote the vectors of this basis as $\vec{n}_i(s, \vec{q}, t)$. $\vec{n}_o$ is the tangent to the centerline. $\vec{n}_1$ and $\vec{n}_2$ are the binormal and normal vectors which reflect the directions of the cross-sectional semimajor and semiminor axes, respectively (see Fig. 2, right).

As the frame is orthonormal, there exists a Darboux vector $\vec{\Omega}(s, \vec{q}, t)$, such that for each $i = 0, 1, 2$:

$$\frac{\partial \vec{n}_i(s, \vec{q}, t)}{\partial s} = \vec{\Omega}(s, \vec{q}, t) \times \vec{n}_i(s, \vec{q}, t)$$

In the local material frame, the coordinates of the Darboux vector $\vec{\Omega}(s, \vec{q}, t)$ are defined as the strand's twist and bend:

$$\vec{\Omega}(s, \vec{q}, t) = \sum_{i=0}^{1} \kappa_i(s, \vec{q}, t)\vec{n}_i(s, \vec{q}, t)$$

Let us now consider one segment S_Q, given by $\langle s_L^Q, s_R^Q \rangle \subseteq \langle 0, L \rangle$.

Recall that each segment of the strand is a plain helix. This means that on S_Q, $\kappa_i(s, \vec{q}, t) = q_{i,Q}(t)$ and is therefore constant with respect to s. So the norm of the Darboux vector $\vec{\Omega}(s, \vec{q}, t)$ is also constant. We denote it $\vec{\Omega}(\vec{q}, t)$. We further introduce the following notations ($\vec{a}$ stands for an arbitrary vector):

$\vec{\omega}(\vec{q}, t) = \dfrac{\vec{\Omega}(\vec{q}, t)}{\Omega(\vec{q}, t)}$	the unit vector parallel to $\vec{\Omega}(\vec{q}, t)$
$\vec{a}^{\parallel} = (\vec{a} \cdot \vec{\omega}(\vec{q}, t)) \cdot \vec{\omega}(\vec{q}, t)$	projection of $\vec{a}$ parallel to $\vec{\omega}(\vec{q}, t)$
$\vec{a}^{\perp} = \vec{a} - \vec{a}^{\parallel}$	projection of $\vec{a}$ perpendicular to $\vec{\omega}(\vec{q}, t)$
$\vec{n}_{i,L}^{Q}(\vec{q}, t) = \vec{n}_i(s_L^Q, \vec{q}, t)$	material frame at segment start
$\vec{r}_L^{Q}(\vec{q}, t) = \vec{r}(s_L^Q, \vec{q}, t)$	centerline position at segment start

The position of the centerline can be then expressed as:

$$\begin{aligned}\vec{r}(s, \vec{q}, t) &= \vec{r}_L^Q(\vec{q}, t) + \big(s - s_L^Q\big)\vec{n}_{0,L}^{Q\parallel}(\vec{q}, t) \\ &\quad + \frac{\sin((s - s_L^Q)\Omega(\vec{q}, t))}{\Omega(\vec{q}, t)}\vec{n}_{0,L}^{Q\perp} \\ &\quad + \frac{1 - \cos((s - s_L^Q)\Omega(\vec{q}, t))}{\Omega(\vec{q}, t)}\big(\vec{\omega}(\vec{q}, t) \times \vec{n}_{0,L}^{Q\perp}\big)\end{aligned}$$

A straight, untwisted segment presents a special case. For such a segment, $\Omega(\vec{q}, t) = 0$, and the above formula is replaced by:

$$\vec{r}(s, \vec{q}, t) = \big(s - s_L^Q\big)\vec{n}_{0,L}^{Q}(\vec{q}, t)$$

4.2 Hair strand dynamics

To derive equations of motion for our model, we use Lagrangian mechanics, with the vector $\vec{q}$ used as generalized coordinates of the model. This gives us the following system of $2N$ equations:

$$\begin{aligned}&\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_{i,Q}}\right) - \frac{\partial T}{\partial q_{i,Q}} + \frac{\partial U}{\partial q_{i,Q}} + \frac{\partial D}{\partial \dot{q}_{i,Q}} \\ &\quad = \int_0^L \frac{\partial \vec{r}_i(s, \vec{q}, t)}{\partial q_{i,Q}} \cdot \vec{F}(s, t)\, ds\end{aligned}$$

for $i = 0, 1$ and $1 \le Q \le N$. The dot accent denotes differentiation by time: $\dot{q}_{i,Q}(t) = \frac{d}{dt} q_{i,Q}(t)$. T, U and D represent the strand's kinetic, potential and dissipation energy, respectively. $\vec{F}(s, t)$ accounts for any external force acting on the strand. In our current model, it consists of gravity, viscous drag from surrounding air (which is considered immobile) and haptic interaction force:

$$\vec{F}(s, t) = m(s)\vec{g} - \nu\dot{\vec{r}}(s, \vec{q}, t) + \vec{F}_{\text{hap}}$$

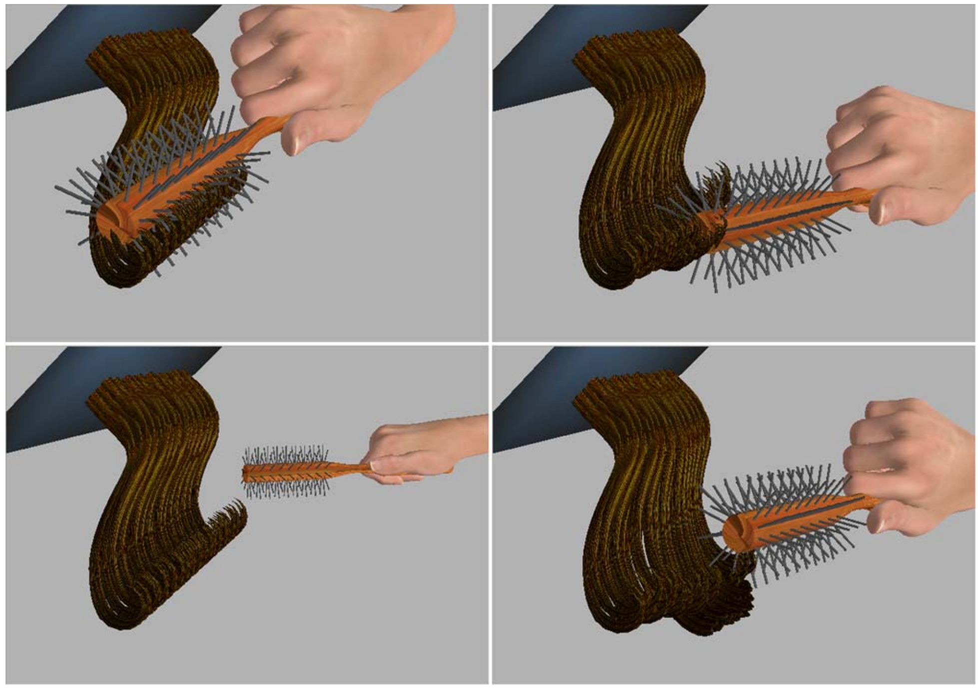

Fig. 3 Experimental setup testing the local interaction model

where $m(s)$ is hair strand mass, $\vec{g}$ is gravitational acceleration, ν is air drag coefficient and $\vec{F}_{\text{hap}}$ is haptic interaction force.

4.3 Local haptic interaction

Tool-hair collisions are computed according to axis-aligned bounding boxes (around the hair strand's segment) and the tool mesh. The material stiffness is calculated considering the specific weight w and cross-sectional area A of the hair fiber and the distance l between the hair root and the collision point. Hence, the haptic interaction force $\vec{F}_{\text{hap}}$ can be computed from the tool velocity $\dot{\vec{t}}$ ($\perp$ denotes the perpendicular projection to the strand tangent $\vec{n}_0$):

$$\vec{F}_{\text{hap}} = \dot{\vec{t}}^{\perp} \frac{wA}{l}$$

Figure 3 depicts the haptic interaction with individual hair strands in an experimental setup.

5 Global dynamics layer

The global layer is responsible for the overall behavior of the full hairstyle. The large-scale simulation model handles hair dynamics, collision handling and interaction tools at a global level. Important optical effects are visualized through an efficient rendering model displaying local specular highlights and global self-shadow, taking into consideration multiple scattering as described in [21].

5.1 Hair lattice

The hairstyle motion is defined by the volume behavior of hair strands. It is controlled by an improved lattice-based free-form deformation model as introduced in [11]. A cubic lattice defines a true volume around the skull (see Fig. 4), and any location inside this volume can be computed using a simple interpolation formula. Hair is attached through viscoelastic forces to the lattice, which is deformed as a particle system.

5.2 Collision handling

Collisions between the *hair* and the *body* are handled by approximating the body as a set of metaballs. These apply a repulsive force field on the nodes of the hairstyle's lattice. In the case the arising forces are too high, an attractive force "stabilizes" the hairstyle, preventing disordered behavior.

Collision handling between the *hair* and the *styling tools* shares the metaballs approach. In this case, however, the metaballs are adapted to match the virtual proxy of the haptic device controlling the tool. The hairdryer tool, for example, is endowed with metaballs creating a force field on lattice node close to the tool's position, causing a global motion which prevents contacts between the hair and the hair dryer.

5.3 Hairstyling tools

Our global hairstyling tools can be used to interact with the complete hairstyle on a large-scale level. These tools treat hair as clusters of individual strands to increase efficiency

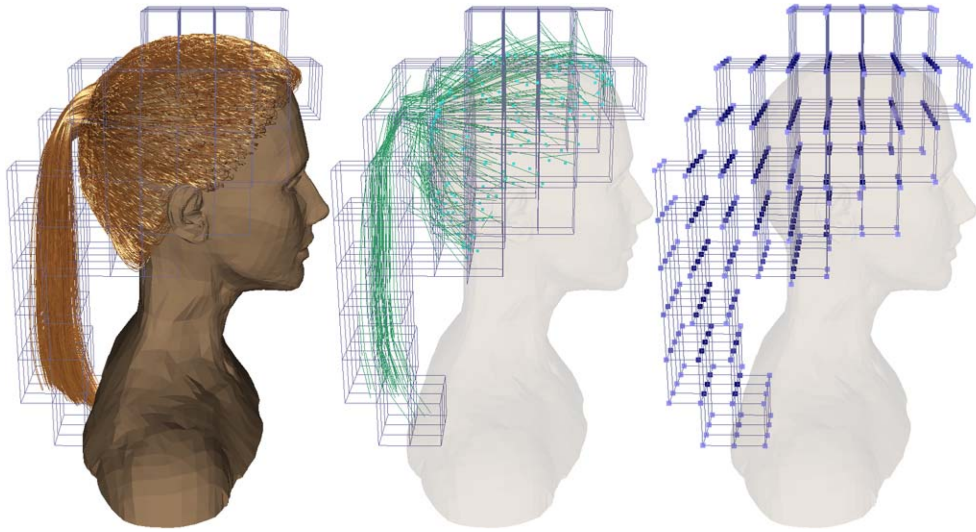

Fig. 4 A hairstyle (*left*) is animated by a mechanical model built using lattice stiffeners (*center*), which also considers hair strand mass (*right*) [11]

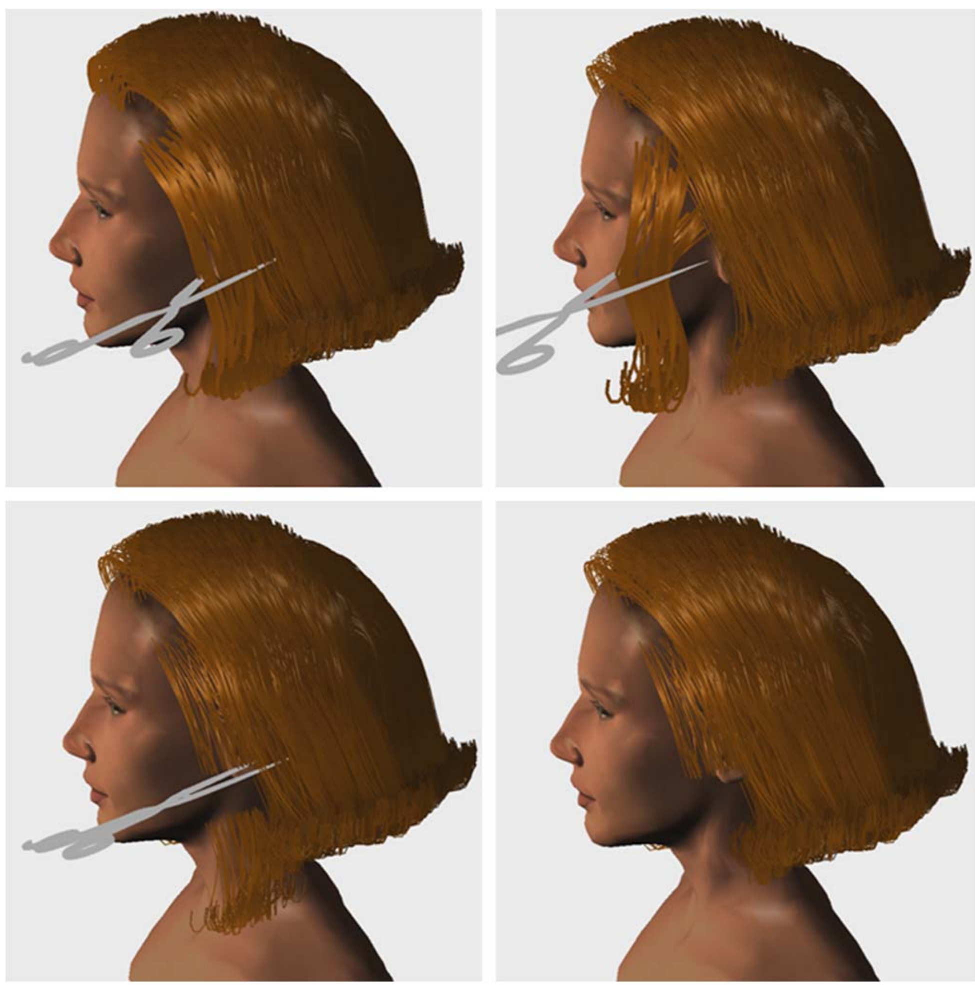

Fig. 5 Image sequence showing the cutting modality. The scissor tool is controlled by a haptic device

in collision detection and reduce computational costs. Several haptic-assisted interactive hair actions such as cutting or drying have been integrated in our virtual hairstyling interface.

Figure 5 shows the cutting mode. When using this interaction modality, hair strands can be cut with a virtual scissor. The cut hair falls down according to a simple mass-spring model which appropriately represents the falling of the hair.

Fig. 6 Image sequence showing our hair dryer tool. The hair wetness is directly influenced by the hair blower, which also creates repulsive forces leaning on the metaball approach

The use of the cluster model for representing the group of cut hair further reduces the geometric complexity and increases the simulation efficiency. The simulation is applied on the guide hair strands, while the other falling hair strands in the cluster are animated using an interpolation scheme. For a random and naturally looking fall of hair we add a noise vector to all the hair in the cluster.

The hair drying modality is depicted in Fig. 6. Unlike a similar tool described in [12], we control the hair dryer through a haptic device. The hair's "look and feel" is controlled by a wetness factor influencing the specularity of the water layer on hair strands through a parameter-controlled Gaussian-based model, as introduced by [22]. The position, orientation and motion of the hair blower directly modify the hair wetness. We find the area of influence and then decrease the wetness of that region. This parameter allows for displaying different degrees of hair wetness in the range of one (wet hair) and zero (dry hair).

The hair drying tool also influences the hair motion during drying. Hair clusters are animated according to the metaballs located in the hairdryer tool. These create a repulsive force field on the nodes of the lattice and efficiently approximate the effect of hair blown by the hair dryer.

A number of additional hair interaction tools can be easily added, e.g. the hair drying can be complemented by a hair wetting tool.

6 Conclusion and future work

We have presented a multilayered simulation framework for visuo-haptic interaction with virtual hair. Two layers handle the hair simulation and the response to the user interaction at a local and at a global level. They specifically address the requirements of vision and haptics and run at different rates.

Our local interaction layer models the contact between the users tool (e.g. a brush) and individual hair strands according to a simple and fast model based on segmented helical rods. Moreover, it computes local contact forces according to haptically relevant hair properties. Our modeling of the mechanical behavior and the haptic perception of individual hair strands is carried by studies on real physical hair properties investigating hair mechanics and handling.

Our global dynamics layer is responsible for the overall behavior of the full hairstyle. The large-scale simulation model handles hair dynamics, collision handling and interaction tools at a global level. Hair interaction tools are optimized for their respective layers, with combing tools affecting the local model, and cutting/drying tools acting on the global model.

6.1 Implementation

The implementation is done in standard C++. For the local interaction model, we used the symbolic math toolbox of the Matlab program to obtain the equations of motion. These are then integrated using DASPK, a differential algebraic equation solver [23]. Part of the implementation of the haptic control is based on CHAI3D [24]. This allows us to support most commercial haptic devices based on impedance control. We tested the described system with different haptic devices, such as a Force Dimension Omega and a Sensable Phantom Desktop. Enhanced control over the VR world and the virtual head is provided by the use of a 3D Connexion Spaceball 5,000.

6.2 Future work

Although the presented system provides interesting results in terms of methodology and hair interaction modalities, there are still several steps needed in order to achieve a hairstyling framework offering a complete set of functionalities which could be compared to a real hair saloon and validated accordingly. Necessary advancements include, among others:

- Enhanced synchronization of local and global layers. While a naïve integration approach alternating the two models by stopping the respective simulation thread is easily achieved, an enhanced synchronization taking more appropriately into account all interdependencies between the models represents a challenging task but could ensure better coupling results.
- High-level definition of individual and collective hair properties (e.g. "curliness" and "combing ease"), influencing visual and haptic rendering.
- Improved contact handling modeling the effects of the brush torque on individual hair strands and allowing to interactively define a fixed strand's position.

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